A System Dynamics Model of the Air Transport System

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In this report, we give a complete algebraic description of a system dynamics model of the air transport system, developed to assess the impact of different policies on the adoption rate of fully electric aircraft until the year 2050. Our model consists of the interaction between three major segments, namely air travel demand, airline industry and aircraft manufacturers.

This model was used in the paper "How much can electric aircraft contribute to reaching the Flightpath 2050 CO_2 emissions goal? A system dynamics approach for European short haul flights" for the computational results therein.

Keywords – Flightpath 2050, Electric aircraft, Air transport system, System dynamics, Short haul flight

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1 Model Explanation

In this section, an overview of the system dynamics air transport (ATS) model structure and its boundaries are explained. The model structure includes the major aspects of the air transport system that have been considered for developing the model.

Model Structure

The ATS model consists of three major segments: air travel demand, the airline industry and aircraft manufacturers. The interaction between these segments is defined by ordinary differential equation (ODE) and partial differential equation (PDE). These equations endogenously interact with each other to mimic the air transport system. There are exogenous parameters like EU GDP per capita and EU population which influence the behavior of the model by providing initial values. Furthermore, the results / outputs of the model consist of the emissions and the electric aircraft technology adoption rate. The model structure is shown in Figure 1.

In Figure 1, the outermost dashed line represents the boundary of the system and denotes the scope of the study. The arrows pointing inward depict exogenous parameters. The interactions between air travel demand, airline industry and aircraft manufacturers generate information about the system (arrows pointing outwards). The basic functioning of the system starts with the formation of air travel demand, which is then processed by the airlines to calculate the required fleet. To expand their fleet, the airlines order new aircraft from the manufacturer. Depending on the cost advantage and policy conditions, the airlines order either conventional or electric aircraft. These orders are realized by the aircraft manufacturers after taking into account production capacities and delivery bottlenecks. After the aircraft are delivered, they are then operated by the airlines. The

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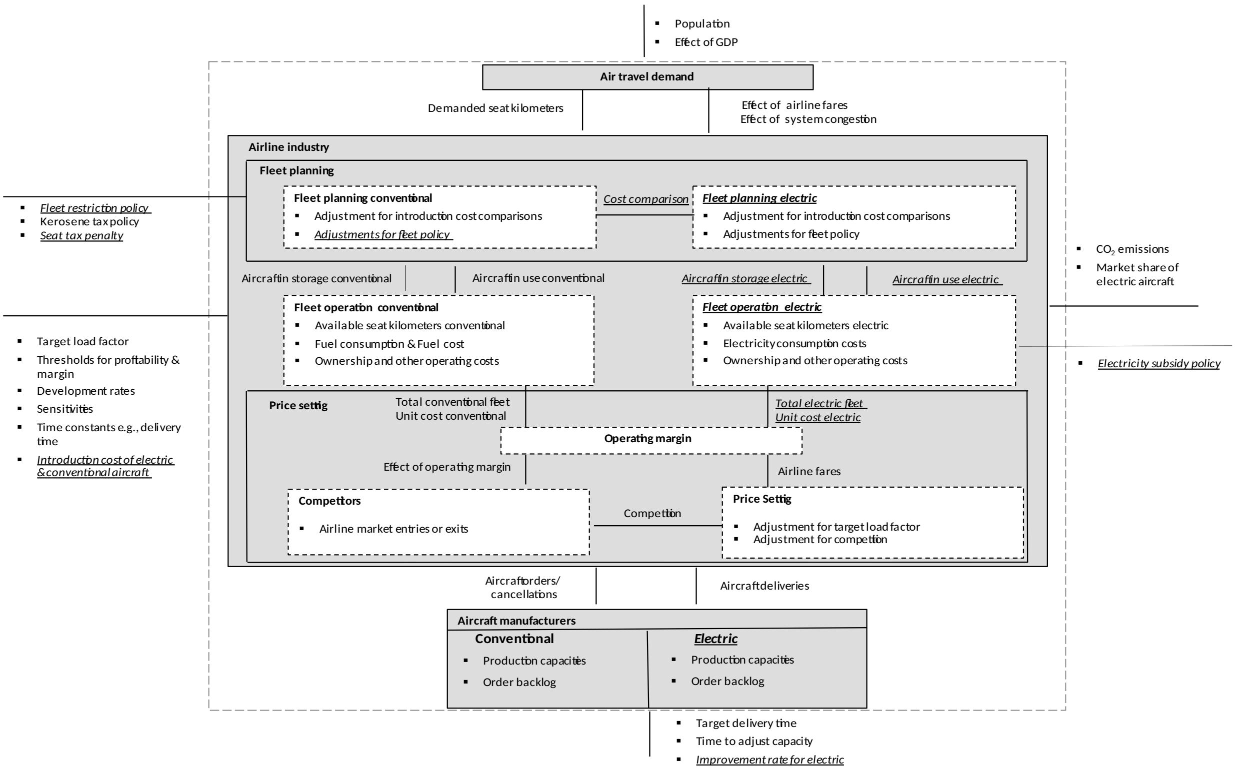

Figure 1: Overview of the ATS model. Based on [3]; segments and variables in underlined italics represent extensions of the original model.

cost of operation of the fleet and revenue obtained together generate the operating margin. Furthermore, the effect of operating costs, competition and load factor influences the airline fares. The airline fares along with the congestion, in turn, affect the air travel demand.

In the above mentioned process, the CO_2 emissions are generated based on the active conventional fleet.

Policies

Different policies have been implemented: jet fuel tax, electricity subsidy, seat tax, government fleet restriction policy, as well as combinations of these.

Model Boundaries

In order to not let the ATS model become too complex, it is important to set limits on the scope of the model. Table 2 shows the overview of model boundaries by listing the most relevant endogenous, exogenous and not considered variables.

2 Algebraic Model Description

In the following section, the system dynamics ATS model is described in detail with its algebraic equations. The variable names and modeling techniques follow [3, 4].

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Table 2: Model variables

Endogenous variables	Exogenous variables	Not considered
Demand	Demand for flight distance	Demand migration
Forecasted demand	GDP per capita	Long-haul flights
Seat load factor	Target load factor	Long-haul feeder flights
Ticket prices	Electricity prices	Financing fees
Unit costs (operations)	Starting value for costs	Aircraft leasing
Operating margin	EU population	Certificate trading (ETS)
Number of competitors	Threshold value for operating margin	Airline company type
New aircraft order rate	Consumer price index (CPI)	Slot management
Aircraft in operation	Oil prices	Airport charging time
Aircraft in storage	Electric flight range	Infrastructure for battery charging
Aircraft manufacturing capacity	Time for capacity changes	Extreme incidents (e.g., 9/11)
Delivery of aircraft	Year of introduction of electric aircraft	Scarcity of resources (e.g., lithium)
Fuel consumption	Technical development rate	Battery development
Share of electric aircraft	Sensitivities	Capacity limitation of airports
CO_2 emissions	Battery power consumption	Different processes for battery development
Operated seat kilometers	Taxes and subsidy rates	Emission compensations
Order rates	Average flight distance	Alternative drive systems (e.g., hydrogen)
Aircraft delivery rates	Fleet restriction policy values	Production emissions
Supply line adjustment time	Time to perceive costs	Emissions of further pollutants

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2.1 Demand for Air Transport

The modeling of the demand for air transport is based on the works of [3, 4] and no further extensions were made in this element of the model. The demand $D(t)$ for air transport depends on the development of the factors effect of European GDP per capita $E^{\text{GDP}}(t)$ and the population size $P(t)$. Furthermore, the demand formulation also includes an initial comparative demand D^{ref} per capita, fares $E^{\text{AF}}(t)$ and congestion of the system $E^{\text{CG}}(t)$ and is given as

$$D(t) = P(t) \cdot D^{\text{ref}} \cdot E^{\text{GDP}}(t) \cdot E^{\text{AF}}(t) \cdot E^{\text{CG}}(t).$$

Here, the population size is calculated exogenously, whereas the effects of GDP, fares and system congestion are determined endogenously in the model. The GDP and fare effect are determined by dividing the reference value to the current value

$$E^{\text{GDP}}(t) = \left(\frac{GDP(t)}{GDP^{\text{ref}}(t)}\right)^{\gamma^{\text{GDP}}}, \qquad E^{\text{AF}}(t) = \left(\frac{AF(t)}{AF^{\text{ref}}(t)}\right)^{\gamma^{\text{AF}}}.$$

The system congestion is determined by comparing the currently perceived seat load factor $PLF(t)$ with the target load factor $TLF(t)$, where $PLF(t)$ is determined with a time delay τ^{PLF} from the actual load factor $LF(t)$

$$PLF(t) = \text{smooth}(LF(t), \tau^{\text{PLF}})$$

The smooth function in Vensim maps a time-delayed perception of the actual value [8]. The comparison of both load factors is also modeled with this function, since customers adapt their flight behavior to the system overload after a delay

$$E^{\text{CG}}(t) = \left(\text{smooth}\left(\frac{PLF(t)}{TLF(t)}, \tau^{\text{CG}}\right)\right)^{\gamma^{\text{CG}}}.$$

Here, $\gamma^{\text{GDP}} > 0$, $\gamma^{\text{AF}} < 0$, and $\gamma^{\text{CG}} < 0$ control the demand sensitivity to changes in GDP, fares and system overload, respectively.

2.1.1 Demand Forecast

The airlines monitor passenger demand and calculate a forecast $D^{\text{est}}(t)$, which is used as a basis for fleet planning. For this purpose, the current actual demand is mapped and compared with a previous reference value. A growth rate can be derived from this comparison. Together with the growth rate and the current demand, the forecast $D^{\text{est}}(t)$ is formed.

The currently perceived demand $D^{\text{per}}(t)$ changes depending on the actual demand $D(t)$ and the time τ^{per} that the airline needs to perceive the change in demand

$$\frac{d}{dt} D^{\text{per}}(t) = \frac{D(t) - D^{\text{per}}(t)}{\tau^{\text{per}}}.$$

As a basis for comparison, the variable $D^{\text{ref}}(t)$ is used. The time delay τ^{ref}, which describes the time horizon for measuring growth rates, defines the rate of change of D^{ref}, which is formed analogously,

$$\frac{d}{dt} D^{\text{ref}}(t) = \frac{D^{\text{per}}(t) - D^{\text{ref}}(t)}{\tau^{\text{ref}}}.$$

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With these two values, the perceived demand and the previous reference value, the growth rate $g^{\text{indicated}}(t)$ can be determined,

$$g^{\text{indicated}}(t) = \frac{D^{\text{per}}(t) - D^{\text{ref}}(t)}{D^{\text{ref}}(t) \cdot \tau^{\text{ref}}}.$$

This is then used to calculate the expected growth rate $g^{\text{expect}}(t)$, which is also time-delayed by τ^{g},

$$\frac{d}{dt} g^{\text{expect}}(t) = \frac{g^{\text{indicated}}(t) - g^{\text{expect}}(t)}{\tau^{g}}.$$

In the end, this expected growth rate is used to forecast the future expected demand $D^{\text{est}}(t)$ based on the currently perceived demand $D^{\text{per}}(t)$,

$$D^{\text{est}}(t) = D^{\text{per}}(t) + \left(1 + g^{\text{expect}}(t) \cdot \tau^{\text{per}}\right). \tag{1}$$

2.2 Airline Industry

2.2.1 New Aircraft Order Rate

Based on the forecasted demand, the desired capacity to be fulfilled is calculated. This calculation in particular is kept analogous to [3]. First, the estimated demand in seats $ED(t)$ is determined by dividing the estimated current demand from (1) by the average flight distance of a seat (800 000 km/year),

$$ED(t) = \frac{D^{\text{est}}(t)}{distance^{\text{seat}}}$$

By dividing the estimated demand by the target load factor $TLF(t)$, we obtain the desired capacity

$$DC(t) = \frac{ED(t)}{TLF(t)}.$$

Given the obtained total desired capacity, an extension regarding the split decision is made by the airlines. In order to offer the seats corresponding to the demand, it is important for airlines to distinguish between conventional and electric seats. Thus the desired capacity for conventional is

$$DC_{\text{conv}} = \begin{cases} DC(t), & t < t_{\text{short}}, \\ 0, & t \geq t_{\text{short}},\ IC^{\text{diff}}_{\text{per}}(t) > 0, \\ DC^{\text{policy}}_{\text{conv}}(t), & t \geq t_{\text{policy}},\ IC^{\text{diff}}_{\text{per}}(t) \leq 0,\ t > t_{\text{short}}, \\ DC(t) - DC_{\text{e}}(t), & \text{else}, \end{cases}$$

where t_{policy} is the time of introduction of the government fleet restriction policy and t_{short} is the year of the introduction of electric aircraft in the model. The explanation for the desired capacity for conventional $DC^{\text{policy}}_{\text{conv}}$ in the case of a government fleet policy is given in equations (8) and (9). The perceived introduction cost difference between electric and conventional aircraft is $IC^{\text{diff}}_{\text{per}}$ and is calculated by

$$IC^{\text{diff}}_{\text{per}} = \text{delay}(IC^{\text{diff}}, \tau^{\text{diff}}),$$

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where

$$IC^{\text{diff}} = IC_{\text{e}} - IC_{\text{conv}}$$

and τ^{diff} is the time taken to perceive the cost difference. If $IC^{\text{diff}}(t) > 0$, then introducing an electric aircraft is more expensive than the conventional ones. On the other hand, if $IC^{\text{diff}}(t) < 0$, then electric aircraft have a lower price. The reason to introduce a delay [7] is that the airlines require some time to perceive the introduction cost differences to adjust their future orders.

Together with the currently used aircraft $AU_{\text{conv}}(t)$ and aircraft in storage resumed for service $IS_{\text{conv}}(t)$, the capacity adjustment $CA_{\text{conv}}(t)$ for conventional aircraft is given by

$$CA_{\text{conv}}(t) = \begin{cases} \frac{DC^{\text{per}}_{\text{conv}} - (AU_{\text{conv}}(t) + IS_{\text{conv}}(t))}{\tau^{\text{ca}}}, & t > t_{\text{short}},\ IC^{\text{diff}} < 0,\ DC_{\text{e}}(t) > 0, \\ \frac{DC_{\text{conv}} - (AU_{\text{conv}}(t) + IS_{\text{conv}}(t))}{\tau^{\text{ca}}}, & \text{else.} \end{cases}$$

Here, when the government policy is introduced, the airlines adjust for the desired capacity with respective delays. Furthermore, the capacity adjustment growth $CA^{\text{G}}(t)$ is calculated as

$$CA^{\text{G}}_{\text{conv}} = AU_{\text{conv}}(t) \cdot g^{\text{expect}}(t) \cdot W^{\text{G}},$$

where W^{G} is the weighting factor and $g^{\text{expect}}(t)$ is the expected growth rate of demand.

From the above equations the desired acquisition rate $DAR(t)$ can be determined considering the decommissioned aircraft $RT_{\text{conv}}(t)$ when $IC^{\text{diff}} \geq 0$

$$DAR_{\text{conv}}(t) = \begin{cases} CA_{\text{conv}}(t) + CA^{\text{G}}_{\text{conv}}(t), & IC^{\text{diff}} < 0, \\ CA_{\text{conv}}(t) + CA^{\text{G}}_{\text{conv}}(t) + RT_{\text{conv}}(t), & \text{else.} \end{cases}$$

To accommodate the supply line inventory, we first compute the desired supply line

$$DSL_{\text{conv}}(t) = \tau^{\text{ED}} \cdot DAR_{\text{conv}}(t),$$

where τ^{ED} is the estimated delivery time, which is calculated by dividing ordered seats $SO_{\text{conv}}(t)$ by the delivered seats $DR_{\text{conv}}(t)$,

$$\tau^{\text{ED}}(t) = \frac{SO_{\text{conv}}(t)}{DR_{\text{conv}}(t)}.$$

From here, the supply line adjustment $SLA_{\text{conv}}(t)$ is then given by subtracting the ordered seats $SO_{\text{conv}}(t)$ from the desired supply line $DSL_{\text{conv}}(t)$ and dividing it by τ^{SL}, which is the time taken to adjust for supply line

$$SLA_{\text{conv}}(t) = \frac{DSL_{\text{conv}}(t) - SO_{\text{conv}}(t)}{\tau^{SL}}.$$

The supply line growth adjustment $SLA^{\text{G}}_{\text{conv}}(t)$ is calculated as

$$SLA^{\text{G}}_{\text{conv}}(t) = SO_{\text{conv}}(t) \cdot W^{\text{G}} \cdot g^{\text{expect}}(t).$$

Finally, we calculate the indicated order rate

$$IOR_{\text{conv}}(t) = DAR_{\text{conv}}(t) + SLA_{\text{conv}}(t) + SLA^{\text{G}}_{\text{conv}}(t).$$

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In the same way, the desired capacity for electric aircraft $DC_{\mathrm{e}}(t)$ is given as

$$DC_{\mathrm{e}}(t) = \begin{cases} 0, & t < t_{\mathrm{short}}, \\ DC(t), & t \geq t_{\mathrm{short}},\ IC^{\mathrm{diff}}_{\mathrm{per}}(t) \leq 0, \\ DC^{\mathrm{policy}}_{\mathrm{e}}(t), & t \geq t_{\mathrm{short}},\ IC^{\mathrm{diff}}_{\mathrm{per}}(t) > 0,\ t \geq t_{\mathrm{policy}}, \\ 0, & \text{else.} \end{cases} \tag{2}$$

Here, the variables for the conditions are analogous to the ones used above for conventional aircraft. The capacity adjustment for the electric fleet is then given by

$$CA_{\mathrm{e}}(t) = \frac{DC^{\mathrm{per}}_{\mathrm{e}}(t) - AU_{\mathrm{e}}(t)}{\tau^{\mathrm{CA}}}.$$

The perceived desired capacity $DC^{\mathrm{per}}_{\mathrm{e}}$ refers to the delay that the airlines need to adjust the capacity requirements. Furthermore, the capacity for adjustment is calculated in the same way as for conventional aircraft, with W^{G} as weighting factor and $g^{\mathrm{expect}}(t)$ as expected growth rate of demand,

$$CA^{\mathrm{G}}_{\mathrm{e}}(t) = AU_{\mathrm{e}}(t) \cdot g^{\mathrm{expect}}(t) \cdot W^{\mathrm{G}}.$$

The desired acquisition rate for electric aircraft $DAR_{\mathrm{e}}(t)$ can be determined using the capacity adjustment growth $CA^{\mathrm{G}}_{\mathrm{e}}(t)$ and capacity adjustment $CA_{\mathrm{e}}(t)$,

$$DAR_{\mathrm{e}}(t) = CA_{\mathrm{e}}(t) + CA^{\mathrm{G}}_{\mathrm{e}}(t).$$

The desired supply line for electric aircraft $DSL_{\mathrm{e}}(t)$ is given by

$$DSL_{e}(t) = \tau^{\mathrm{ED}} \cdot DAR_{\mathrm{e}}(t).$$

Using the above, the supply line adjustment for electric aircraft is computed by

$$SLA_{\mathrm{e}}(t) = \frac{DSL_{\mathrm{e}}(t) - SO_{\mathrm{e}}(t)}{\tau^{\mathrm{SL}}}.$$

The supply line adjustment growth for electric aircraft then becomes

$$SLA^{\mathrm{G}}_{\mathrm{e}}(t) = SO_{\mathrm{e}}(t) \cdot W^{\mathrm{G}} \cdot g^{\mathrm{expect}}(t).$$

Finally, the indicated order rate for electric is

$$IOR_{\mathrm{e}}(t) = DAR_{\mathrm{e}}(t) + SLA_{\mathrm{e}}(t) + SLA^{\mathrm{G}}_{\mathrm{e}}(t).$$

2.2.2 Aircraft Life Cycle and Purchase Decisions

The indicated order rate determined in the previous section is now used to calculate the actual order rates, divided into conventional and electric aircraft. For simplicity, the above decisions are kept the same for both types of aircraft. The base of these equations comes again from [3].

The two indicated order rates have to be corrected by the aircraft which are out of service and will be returning into service $RS(t)$. In addition, the order rate OR is set to zero if the previous calculation corresponds to a negative IOR.

$$\begin{aligned} OR_{\mathrm{conv}}(t) &= \max(0, IOR_{\mathrm{conv}}(t) - RS_{\mathrm{conv}}(t)), \\ OR_{\mathrm{e}}(t) &= \max(0, IOR_{\mathrm{e}}(t) - RS_{\mathrm{e}}(t)). \end{aligned}$$

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The change of the ordered seats $SO(t)$ are determined by the order rates, delivery rates $DR(t)$ and cancellations $CX(t)$,

$$\frac{d}{dt}SO_{\text{conv}}(t) = OR_{\text{conv}}(t) - DR_{\text{conv}}(t) - CX_{\text{conv}}(t),$$
$$\frac{d}{dt}SO_{\text{e}}(t) = OR_{\text{e}}(t) - DR_{\text{e}}(t) - CX_{\text{e}}(t).$$

Cancellations are executed if the calculated indicated order rate $IOR(t)$ is negative. Cancellation rates are the minimum of $IOR(t)$ and the ordered seats $SO(t)$ divided by the duration of the cancellation τ^{CX},

$$CX_{\text{conv}}(t) = \begin{cases} \min\left(-IOR_{\text{conv}}(t), \frac{SO_{\text{conv}}(t)}{\tau^{\text{CX}}}\right), & IOR_{\text{conv}}(t) < 0, \\ 0, & \text{else}, \end{cases}$$
$$CX_{\text{e}}(t) = \begin{cases} \min\left(-IOR_{\text{e}}(t), \frac{SO_{\text{e}}(t)}{\tau^{\text{CX}}}\right), & IOR_{\text{e}}(t) < 0, \\ 0, & \text{else}. \end{cases}$$

The delivery rates $DR(t)$ are calculated by dividing the number of ordered seats by the target delivery time τ^{DT} of the aircraft manufacturer. The function is also limited by the manufacturer's capacity $AMC(t)$,

$$DR_{\text{conv}}(t) = \min\left(\frac{SO_{\text{conv}}(t)}{\tau^{\text{DT}}}, AMC_{\text{conv}}(t)\right),$$
$$DR_{\text{e}}(t) = \min\left(\frac{SO_{\text{e}}(t)}{\tau^{\text{DT}}}, AMC_{\text{e}}(t)\right).$$

The delivery rate, together with older aircraft being returned into service, determines the growth in aircraft operated $AU(t)$. Aircraft being decommissioned $RT(t)$[1] or stored $IS(t)$ reduce the number of seats operated by the airline,

$$\frac{d}{dt}AU_{\text{conv}}(t) = DR_{\text{conv}}(t) + RS_{\text{conv}}(t) - IS_{\text{conv}}(t) - RT(t),$$
$$\frac{d}{dt}AU_{\text{e}}(t) = DR_{\text{e}}(t) + RS_{\text{e}}(t) - IS_{\text{e}}(t).$$

The rate $IS(t)$ at which aircraft are taken out of service and parked is determined by the calculated order rate. If $IOR(t)$ is negative, this means that the fleet should be reduced.

Before the introduction of electric aircraft, initiating storage for conventional aircraft depends mainly on the operating margin $OM(t)$. If $OM(t)$ falls below a reference value, $IS(t)$ becomes active. The aircraft taken out of service are the minimum of the indicated order rate or the aircraft in service divided by the time τ^{ISto} it takes to take an aircraft out,

$$IS_{\text{conv}} = \begin{cases} \min\left(-IOR_{\text{conv}}(t), \frac{AU_{\text{conv}}(t)}{\tau^{\text{ISto}}}\right), & IOR_{\text{conv}}(t) < 0,\ OM(t) \leq OM^{\text{ref}} \\ 0, & \text{else}. \end{cases}$$

[1] As there are no plans to decommission electric aircraft in the model's running time until 2050, only conventional aircraft can be decommissioned. Therefore, $RT(t)$ is only modeled for conventional aircraft.

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After the introduction of electric aircraft, the choice made by airlines to store or retire aircraft will depend on $IC^{\text{diff}}(t)$ or the government fleet restriction policy. Initiating storage for conventional aircraft is then

$$IS_{\text{conv}} = \begin{cases} AC^{\text{store}}_{\text{conv}}, & IC^{\text{diff}}(t) > 0, \\ \min\left(-IOR_{\text{conv}}(t), \frac{AU_{\text{conv}}(t)}{\tau^{\text{ISto}}}\right), & IOR_{\text{conv}}(t) < 0,\ DC_{\text{e}} > 0 \\ 0, & \text{else}, \end{cases} \tag{3}$$

where $AC^{\text{store}}_{\text{conv}}$ are the conventional aircraft needed to be stored per year if the government fleet policy is activated. It is calculated as

$$AC^{\text{store}}_{\text{conv}} = \frac{target_{\text{conv}}}{\text{flight distance per seat conventional}}.$$

Here, $target_{\text{conv}}$ is given by

$$target_{\text{conv}} = \begin{cases} \max(\text{ASK}_{\text{conv}} - OB_conv, 0), & t > t_{\text{policy}}, \\ 0, & \text{else}, \end{cases}$$

where $OB_{\text{conv}} = \text{ASK}_{\text{conv}} \cdot multiplier_{\text{conv}}$ is the objective for airlines. The multiplier $multiplier_{\text{conv}}$ depends on the percentage of the government policy. If the government sets a high percentage policy in favor of electric aircraft, the multiplier for conventional will also be higher.

The storage decision for electric aircraft is similar to the conventional one before the introduction of electric aircraft,

$$IS_{\text{e}} = \begin{cases} \min\left(-IOR_{\text{e}}(t), \frac{AU_{\text{e}}(t)}{\tau^{\text{ISto}}}\right), & IOR_{\text{e}}(t) < 0,\ OM(t) \leq OM^{\text{ref}} \\ 0, & \text{else}. \end{cases}$$

The introduction of aircraft back into service from storage is also determined by the calculated order rate $IOR(t)$. If it is positive, the aircraft already owned by the airline will be reactivated. This rate $RS(t)$ is defined by the number of parked aircraft $AS(t)$ divided by the time τ^{ISer} for returning the aircraft into service.

The decision to return conventional aircraft differs if electric aircraft are already introduced or if the government fleet policy is active. Before the introduction of electric aircraft the rate is

$$RS_{\text{conv}}(t) = \begin{cases} \frac{AS_{\text{conv}}(t)}{\tau^{\text{ISer}}}, & IOR_{\text{conv}} > 0, \\ 0, & \text{else}. \end{cases}$$

After the introduction, it is computed by

$$RS_{\text{conv}}(t) = \begin{cases} 0, & IC^{\text{diff}}(t) < 0, \\ \frac{AS_{\text{conv}}(t)}{\tau^{\text{ISer}}}, & IC^{\text{diff}} > 0,\ multiplier_{\text{conv}} < 0, \\ 0, & \text{else}. \end{cases} \tag{4}$$

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For electric aircraft, the rate is

$$RS_{\mathrm{e}}(t) = \begin{cases} \frac{AS_{\mathrm{e}}(t)}{\tau^{\mathrm{ISer}}}, & IOR_{\mathrm{e}} > 0, \\ 0, & \text{else.} \end{cases}$$

After the introduction of electric aircraft, the airlines would also change their decisions regarding retirements. On the one hand, when airlines are forced to store conventional aircraft due to the government fleet policy initiative, the airlines will wait for a certain amount of time before retiring the aircraft permanently from storage.

The retirement from storage $RT^{\mathrm{store}}_{\mathrm{conv}}$ depends on the introduction cost difference $IC^{\mathrm{diff}}(t)$ and the multiplier $multiplier_{\mathrm{conv}}$,

$$RT^{\mathrm{store}}_{\mathrm{conv}}(t) = \begin{cases} \frac{AS_{\mathrm{conv}}(t)}{\tau^{\mathrm{store}}}, & IC^{\mathrm{diff}}(t) < 0 \ \text{ or } \ (IC^{\mathrm{diff}} > 0, \ multiplier_{\mathrm{conv}} > 0), \\ 0, & \text{else.} \end{cases}$$

Here, τ^{store} is the time it takes to retire aircraft from storage.

The retirement of conventional aircraft from active use remains the same and depends on the average aircraft life AVG_{life},

$$RT_{\mathrm{conv}}(t) = \max\left(0, \frac{AU_{\mathrm{conv}}}{AVG_{\mathrm{life}}}\right).$$

2.2.3 Costs, Fuel Consumption and Emissions

The unit costs for conventional aircraft is a combination of fuel costs, ownership costs and operating costs. Ownership costs are costs that are independent of aircraft operations, such as insurance or acquisition costs. Operating costs, excluding fuel costs, are related to the operation of the aircraft and include costs like personnel or airport charges. The modeling of these three costs is taken over from [3]. The cost structure is extended by the costs for electric aircraft including batteries. For simplicity, the operating costs are assumed to be identical to conventional aircraft.

The fuel cost $FU^{\mathrm{FLE}}(t)$ depends on the changes that take place in the fuel consumption per kilometer,

$$\frac{d}{dt}FU^{\mathrm{FLE}}(t) = FU^{\mathrm{NA}}(t) \cdot DR_{\mathrm{conv}}(t) - \frac{FU^{\mathrm{FLE}}(t)}{AU_{\mathrm{conv}}(t)} \cdot RT^{\mathrm{TTL}}_{\mathrm{conv}}(t).$$

$FU^{\mathrm{FLE}}(t)$ is determined by the amount of fuel consumption of the new aircraft deliveries $FU^{\mathrm{NA}}(t) \cdot DR_{\mathrm{conv}}(t)$ minus the fuel consumption of the total number of retired aircraft $RT^{\mathrm{TTL}}_{\mathrm{conv}}(t)$. The total number of retired aircraft include the retirements from storage as well as the direct retirements from usage.

To determine the annual fuel consumption $FU^{\mathrm{ANN}}(t)$, the average fleet consumption per kilometer is multiplied by the average flight distance per seat $distance^{\mathrm{seat}}$,

$$FU^{\mathrm{ANN}}(t) = FU^{\mathrm{FLE}}(t) \cdot distance^{\mathrm{seat}}.$$

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Since the fuel costs are taken over from [3], costs for alternative fuel are also included in the equations. The decision as to which fuel to buy is simply a matter of price and thus determines the desired drop-in rate $AFS^{\mathrm{TAR}}(t)$. If alternative fuels have a cost advantage, it will be used as much as possible, while the annual consumption of alternative fuels $AFU^{\mathrm{ANN}}(t)$ is limited by the production limit $PC(t)$ and the maximum drop-in quota AFQ,

$$AFU^{\mathrm{ANN}}(t) = \min\left(\min(AFS^{\mathrm{TAR}}(t), AFQ) \cdot FU^{\mathrm{ANN}}(t), PC(t)\right).$$

This can then be used to calculate the annual emissions

$$E^{\mathrm{ANN}}(t) = \left(FU^{\mathrm{ANN}}(t) - AFU^{\mathrm{ANN}}(t) \cdot MP\right) \cdot EI,$$

where MP is the savings potential of alternative fuels and EI is the emission index of conventional fuel.

The battery costs $BC(t)$ for electric aircraft are calculated by multiplying the electricity consumption per seat kilometre $BEC^{\mathrm{ASK}}(t)$ by the electrically offered seat kilometres $ASK_{\mathrm{e}}(t)$ and the electricity price. The electricity price $ER(t)$ is reduced by the corresponding subsidy $Sub^{\mathrm{ER}}(t)$,

$$BC(t) = BEC^{\mathrm{ASK}}(t) \cdot ASK_{\mathrm{e}}(t) \cdot \left(ER(t) - Sub^{\mathrm{ER}}(t)\right). \tag{5}$$

Together with the ownership costs $OC_{\mathrm{e}}^{\mathrm{seat \cdot km}}(t)$ and the operational costs $OOC^{\mathrm{ASK}}(t)$, the costs per unit for an electric seat-kilometer can be determined by

$$UC_{\mathrm{e}}(t) = OC_{\mathrm{e}}^{\mathrm{seat \cdot km}}(t) + OOC^{\mathrm{ASK}}(t) + \frac{BC(t)}{ASK_{\mathrm{e}}(t)}.$$

The conventional unit costs $UC_{\mathrm{conv}}(t)$ are calculated in the same way; the required fuel costs are defined in (7). Both unit costs are now used to calculate the average cost of a seat kilometre on the basis of the proportion of electric seat kilometres $ASK_{\mathrm{e}}^{\mathrm{ratio}}(t)$,

$$UC^{\mathrm{avg}}(t) = ASK_{\mathrm{e}}^{\mathrm{ratio}}(t) \cdot UC_{\mathrm{e}}(t) + \left(1 - ASK_{\mathrm{e}}^{\mathrm{ratio}}(t)\right) \cdot UC_{\mathrm{conv}}(t).$$

These average costs are used to determine the airline's fares in a later section.

2.2.4 Cost Comparison of Conventional and Electric Aircraft

In order to decide whether to order conventional or electric aircraft, the costs of a unit are compared at the time of the purchase decision. The relative difference of the introduction costs $IC^{\mathrm{diff}}(t)$ is calculated as

$$IC^{\mathrm{diff}}(t) = IC_{\mathrm{e}}(t) - IC_{\mathrm{conv}}(t).$$

The introduction costs $IC_{\mathrm{conv}}(t)$ for conventional is determined by adding fuel costs, operational costs $OOC^{\mathrm{ASK}}(t)$ and ownership costs $OC_{\mathrm{conv}}^{\mathrm{seat \cdot km}}(t)$. $FU_{\mathrm{NA}}(t)$ is the fuel consumption of new aircraft, $AFS(t)$ is the share of alternative fuels, $AFP(t)$ is the price of alternative fuels and $CFP(t)$ is the price of conventional kerosene,

$$\begin{aligned} IC_{\mathrm{conv}}(t) = {} & FU_{\mathrm{NA}}(t) \cdot AFS(t) \cdot AFP(t) + FU_{\mathrm{NA}}(t) \cdot (1 - AFS(t)) \cdot \left(CFP(t) + Tax^{\mathrm{fuel}}(t)\right) \\ & + OOC^{\mathrm{ASK}}(t) + OC_{\mathrm{conv}}^{\mathrm{seat \cdot km}}(t). \end{aligned}$$

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Ownership cost per seat-kilometer $OC_{\text{conv}}^{\text{seat}\cdot\text{km}}(t)$ is determined by the ownership cost per new seat divided by the average annual flight distance of a seat,

$$OC_{\text{conv}}^{\text{seat}\cdot\text{km}}(t) = \frac{OC_{\text{conv}}^{\text{year}}(t)}{distance_{\text{conv}}^{\text{seat}}}.$$

The introduction costs for electric aircraft $IC_{\text{e}}(t)$ consist of electricity costs, which result from the battery consumption $BEC^{\text{ASK}}(t)$ and the electricity price $ER(t)$ minus the subsidies $Sub^{\text{ER}}(t)$ if offered by the government,

$$IC_{\text{e}}(t) = BEC^{\text{ASK}}(t) \cdot \left(ER(t) - Sub^{\text{ER}}(t)\right) + OOC^{\text{ASK}}(t) + OC_{\text{e}}^{\text{seat}\cdot\text{km}}(t).$$

The electric ownership costs per seat-kilometer are calculated analogously to the conventional ones,

$$OC_{\text{e}}^{\text{seat}\cdot\text{km}}(t) = \frac{OC_{\text{e}}^{\text{year}}(t)}{distance_{\text{e}}^{\text{seat}}}.$$

2.2.5 Fare Setting

The airline's fare calculation is implemented with an anchor and adjustment heuristic, similar to [4]. Within the framework of revenue management, the airline determines a price $AF^{\text{ref}}(t)$ for which it currently would like to sell the ticket. The actual price $AF(t)$ will be adjusted within the time τ^{AF},

$$\frac{d}{dt}AF(t) = \frac{AF^{\text{ref}}(t) - AF(t)}{\tau^{\text{AF}}}.$$

The actual fares $AF(t)$ form the anchor on the basis of which the desired fares are determined. The rates are adjusted with regard to the costs $A^{\text{UC}}(t)$, competitors $A^{\text{C}}(t)$ and load factor $A^{\text{LF}}(t)$,

$$AF^{\text{ref}}(t) = AF(t) \cdot A^{\text{UC}}(t) \cdot A^{\text{C}}(t) \cdot A^{\text{LF}}(t).$$

The adjustment for cost changes $A^{\text{UC}}(t)$ is based on a comparison of a minimum fare with the current fare. If the minimum fare is higher than the current fare, it will be increased. A minimum fare is determined by adding a minimum margin PR^{min} to the cost per passenger. For this purpose, the costs per passenger are determined by dividing the average unit cost $UC^{\text{avg}}(t)$ by the load factor. Here, the perceived load factor is used to consider that the airlines also perceive the load factor with a time delay. For comparison, this minimum fare is set in relation to the actual fare $AF(t)$,

$$A^{\text{UC}}(t) = \left(\frac{UC^{\text{avg}}(t)}{PLF(t)} \cdot \frac{1 + PR^{\text{min}}}{AF(t)}\right)^{\gamma^{\text{UC}}}$$

The adjustment to competitors is obtained by comparing the current number of other airlines $NC(t)$ with a reference value $NC^{\text{ref}}(t)$. By assumption, the fare will decrease if there are more competitors in the market and increase if there are fewer airlines,

$$A^{\text{C}}(t) = \left(\frac{NC(t)}{NC^{\text{ref}}(t)}\right)^{\gamma^{\text{C}}}.$$

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The booking situation is taken into account by the factor $A^{\mathrm{LF}}(t)$. If the load factor of the flights is too low, i.e., the perceived load factor $PLF(t)$ is lower than the target load factor $TLF(t)$, a lower ticket price results in more demand and thus a higher load factor. Similarly, as soon as the desired capacity utilization is reached, the ticket price will be raised in order to generate more revenue,

$$A^{\mathrm{LF}}(t) = \left(\frac{PLF(t)}{TLF(t)}\right)^{\gamma^{\mathrm{LF}}}.$$

The factors $\gamma^{\mathrm{UC}} > 0$, $\gamma^{\mathrm{C}} < 0$, and $\gamma^{\mathrm{LF}} > 0$ reflect the sensitivity of the fares to changes in costs, competitors and capacity utilization. The number of competitors $NC(t)$ is determined by the number of airlines $AME(t)$ entering or leaving the market. This depends on the effect of the operating margin $E^{\mathrm{OM}}(t)$ and the time τ^{E} it takes to launch or close an airline,

$$\frac{d}{dt}NC(t) = AME(t),$$
$$AME(t) = \frac{E^{\mathrm{OM}}(t)}{\tau^{\mathrm{E}}}.$$

The effect of the operating margin is determined by comparing the perceived operating margin $OM^{\mathrm{per}}(t)$ with a comparative value at which airlines intend to enter the market,

$$E^{\mathrm{OM}}(t) = \left(\frac{OM^{\mathrm{per}}(t)+1}{OM^{\mathrm{ref}}+1}\right)^{\gamma^{\mathrm{OM}}} - 1.$$

Here, $\gamma^{\mathrm{OM}} > 0$ is the sensitivity to the effect of the operating margin on the entry and exit of airlines. As a result, a high operating margin leads to a positive $AME(t)$ rate, which models the market entry of additional airlines.

2.3 Aircraft Manufacturer

The modeling of aircraft manufacturers was taken over from [3]. It is based on a given delivery time τ^{DT}, in which the orders are to be executed. Therefore, the targeted manufacturing capacity $TMC(t)$ is calculated from the open orders $SO_{\mathrm{conv}}(t)$, which are divided by the delivery time,

$$TMC(t) = \frac{SO_{\mathrm{conv}}(t)}{\tau^{\mathrm{DT}}}.$$

The actual manufacturing capacity $AMC(t)$ is adjusted to the target capacity $TMC(t)$ within a period τ^{MC}, which describes the duration of the capacity adjustment process. Thus, the rate of change for the actual manufacturing capacity $AMC(t)$ is the difference between this and the target capacity $TMC(t)$, divided by the specified time period,

$$\frac{d}{dt}AMC(t) = \frac{TMC(t) - AMC(t)}{\tau^{\mathrm{MC}}}.$$

The manufacturing of electric aircraft is modeled analogous to the conventional ones. In addition, the capacity modeling for the manufacturing of electric aircraft $AMC_{\mathrm{e}}(t)$ is supplemented by

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a jump function and will only be possible when the introduction year for the aircraft is reached, i.e., the year 2035,

$$TMC(t) = \frac{SO_e(t)}{\tau_e^{DT}},$$

$$\frac{d}{dt}AMC_e(t) = \begin{cases} \frac{TMC_e(t)-AMC_e(t)}{\tau_e^{MC}}, & t \geq t_{short}, \\ 0, & \text{else.} \end{cases}$$

Furthermore, we take into account that the manufacturing process of the new type of aircraft has just been started and therefore the capacity cannot be increased as quickly as for conventional aircraft. For this reason, instead of a constant time τ^{MC} for capacity adjustments, a decreasing function for τ_e^{MC} is introduced. This starts with a higher value and decreases over time due to improvements $I_e(t)$ (see (6)) of electric aircraft,

$$\tau_e^{MC} = \tau_e^{MC,t_0} \cdot I_e(t).$$

2.4 Tax and Subsidy

The price of electricity used to charge the batteries is subsidized. This subsidy option was already included in the computation of the battery costs described in (5).

In addition to subsidies, there is also the kerosene/jet fuel tax as a political incentive measure to promote the usage of electric technology. By taxing the jet fuel, it can make the conventional aircraft less attractive [1, 2]. This is implemented by a volume tax $tax^{fuel}(t)$ on kerosene/jet fuel when calculating the fuel costs $FC(t)$. $FC(t)$ is composed of the costs of alternative and conventional fuels, taking into account the share of alternative fuels $AFU^{ANN}(t)$ in the total jet fuel consumption $FU^{ANN}(t)$,

$$FC(t) = AFU^{ANN}(t) \cdot AFP(t) + \left(FU^{ANN}(t) - AFU^{ANN}(t)\right) \cdot \left(CFP(t) + tax^{fuel}(t)\right).$$

2.5 Exogenous Parameters

The model considers technological and structural developments along with the cost reductions. This is applied to conventional and electric airplanes analogously. A constant rate of improvement IR and time τ^{IR}, in which this improvement is achieved, determines how fast the improvement $I(t)$ takes place,

$$\frac{d}{dt}I(t) = I(t) \cdot \frac{IR}{\tau^{IR}}. \tag{6}$$

$I(t)$ has an initial value of 1 and decreases with time. Thus, the factor can be multiplied as a technological improvement to corresponding variables to reduce their values over time.

For conventional aircraft this is the case for the fuel consumption of a new aircraft,

$$FU^{NA}(t) = FU^{NA}(0) \cdot I(t). \tag{7}$$

Ownership cost per seat is based on a constant initial value OC_e^{init} per seat kilometer, which is then multiplied by the average lifetime of an aircraft AC_e^{L} and the flight distance per seat $distance_e^{seat}$.

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These costs only arise when the electric aircraft are available. Here, the improvement effect $I_e(t)$ is directly multiplied. In this case, the improvements are assumed to occur in the form of economies of scale, which reduce the ownership costs over time,

$$OC_e(t) = \begin{cases} AC_e^L \cdot distance_e^{seat} \cdot OC_e^{init} \cdot I_e(t), & t \geq t_{short}, \\ 0, & \text{else.} \end{cases}$$

The conventional ownership costs are formed analogously and increase with the consumer price index CPI. A cost reduction through technical developments is not assumed in this case,

$$OC_{conv}(t) = AC_{conv}^L \cdot distance_{conv}^{seat} \cdot OC_{conv}^{init} \cdot CPI.$$

The range of electric aircraft $range(t)$ is modeled as a jump function, which becomes active as soon as the short-haul electric aircraft is available,

$$range(t) = \begin{cases} range_{short}, & t \geq t_{short}, \\ 0, & \text{else.} \end{cases}$$

2.6 Government Fleet Restriction Policy and Penalty Costs

The government fleet restriction policy is an initiative in which the government mandates that a certain amount of operated fleet has to be electric. In this way the airlines reduce their conventional fleet and increase the desired capacity for electric fleet, as explained in (2). If the government fleet restriction policy had not been introduced then the airlines would make their decisions to order more electric aircraft solely based on the introduction cost difference IC^{diff}, after the introduction of electric aircraft. The fleet policy forces the airlines to adopt electric aircraft even if they are not cost competitive.

First, the airlines calculate the amount of conventional that has to be put in storage to be replaced by electric aircraft,

$$AC_{conv}^{store} = \frac{target_{conv}}{\text{flight distance per seat conventional}},$$

where

$$target_{conv} = \begin{cases} \max(ASK_{conv} - OB_{conv}, 0), & t > t_{policy}, \\ 0, & \text{else,} \end{cases}$$

and OB_{conv} is the objective for the airlines,

$$OB_{conv} = ASK_{conv} \cdot multiplier_{conv}.$$

The multiplier depends on the percentage of the government policy. If the government sets a high percentage policy in favor of electric aircraft, the multiplier for conventional will also be higher. These particular seats will then be put into storage by the conditions set in (3). Furthermore, these aircraft will only return into service under the condition set in equation (4).

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After storing the conventional aircraft, the airlines make changes in their fleet ordering,

$$DC_{\mathrm{e}}^{\mathrm{policy}}(t) = \begin{cases} DC(t) \cdot multiplier^{\mathrm{policy}}, & t > t_{\mathrm{short}}, \\ 0, & \text{else}, \end{cases} \tag{8}$$

where the multiplier $multiplier^{\mathrm{policy}}$ is the percentage mandate the government has imposed on the airlines. $DC_{\mathrm{conv}}^{\mathrm{policy}}$ is now calculated by subtracting the above calculated fleet policy ordering from the actual desired capacity,

$$DC_{\mathrm{conv}}^{\mathrm{policy}} = DC(t) - DC_{\mathrm{e}}^{\mathrm{policy}}(t). \tag{9}$$

As a result of implementing the fleet restriction policy, the stored conventional aircraft would incur costs for the airlines, by losing the profits which those aircraft could have made if they were operational. This storage opportunity cost lost is also added in the unit cost for conventional aircraft. Furthermore, as the government fleet policy is incomplete in itself, the government introduces a seat tax in order to incentivize the airlines to adopt more electric aircraft. In this seat tax, the airlines are obliged to pay a certain amount for every seat that is operated on a conventional aircraft. Both above mentioned aspects are given as

$$UC_{\mathrm{conv}} = \begin{cases} \frac{FC(t)+OOC^{\mathrm{ASK}}(t)+storage^{\mathrm{per}}(t)}{ASK_{\mathrm{conv}}(t)} + OC_{\mathrm{conv}}(t) + penalty^{\mathrm{per}}(t), & t > t_{\mathrm{short}}, \\ \frac{FC(t)+OOC^{\mathrm{ASK}}(t)}{ASK_{\mathrm{conv}}(t)} + OC_{\mathrm{seat}}, & \text{else}. \end{cases}$$

In this equation, $storage^{\mathrm{per}}$ is the perceived storage costs and $penalty^{\mathrm{per}}$ is the perceived penalty costs. Here, perceived means a delay where the airlines need some time to compute and comprehend these costs. The computation of $storage^{\mathrm{per}}$ is given as

$$profit^{\mathrm{TTL}}(t) = revenue^{\mathrm{TTL}}(t) - costs^{\mathrm{TTL}}(t),$$

where $revenue^{\mathrm{TTL}}$ is the total revenue generated by airlines per year and $costs^{\mathrm{TTL}}$ is the total costs of operating the fleet in a given year. From the profit, we can now determine the profit per seat $profit_{\mathrm{seat}}$ by dividing it by the total fleet ASK^{TTL},

$$profit_{\mathrm{seat}}(t) = \frac{profit^{\mathrm{TTL}}(t)}{ASK^{\mathrm{TTL}}(t)}.$$

From here, we can determine the opportunity cost lost by not making the profits for the aircraft put into storage,

$$storage^{\mathrm{TTL}}(t) = AS_{\mathrm{conv}}(t) \cdot profit_{\mathrm{seat}}(t).$$

After delays, $storage^{\mathrm{TTL}}$ becomes $storage^{\mathrm{per}}$.

Now for the computation of the penalty costs, the penalty fee per year $penalty_{\mathrm{year}}$ is dependent on the condition that it is introduced at the same time as the introduction of the government fleet policy and that the operated electric fleet is smaller than requested by the specified percentage,

$$penalty_{\mathrm{year}}(t) = \begin{cases} fee, & t > t_{\mathrm{policy}},\ ASK_{\mathrm{e}}^{\mathrm{ratio}} < multiplier_{\mathrm{policy}}, \\ 0, & \text{else}. \end{cases}$$

Here, *fee* is the corresponding exogenous parameter. Furthermore, after some delay, the penalty per year $penalty_{\mathrm{year}}$ becomes the perceived penalty $penalty^{\mathrm{per}}$.

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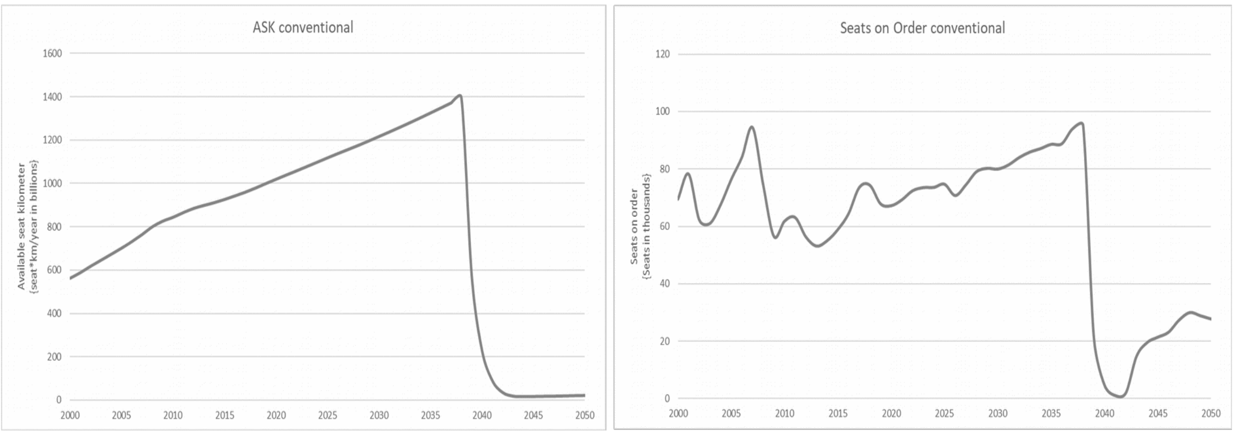

Figure 3: Results of extreme policy: 90 % fleet restriction.

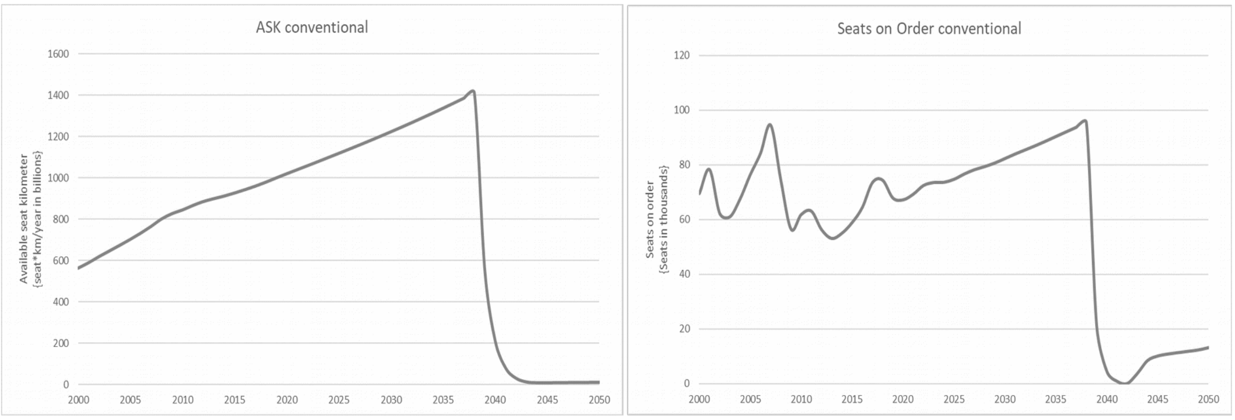

Figure 4: Results of extreme policy: 95 % fleet restriction.

3 Model Validation: Extreme Policy Tests

In this section, some extreme policy test scenarios are discussed. Figure 3 depicts the observed variables ASK conventional and seats on order conventional for a 90 % fleet restriction policy. It can be observed that none of the variables take a negative value after the introduction of the policy in the year 2038. Instead, it shows that the conventional fleet is immediately reduced to meet the restriction goals. The above suggests that the two observed model variables are showing reasonable behavior in extreme conditions [5].

Figure 4 depicts the variables for the 95 % fleet restriction policy in the model. Similar to the above results, the model seems to be behaving reasonably in this particular policy scenario. The only observable difference is that the rise in ordered seats after the policy goal is reached is lower in this policy than in the 90 % fleet restriction policy.

Lastly, Figure 5 depicts the high subsidy extreme policy. In this case, due to the high subsidy rates, the electric fleet becomes highly attractive for the airlines, while the conventional fleet becomes less attractive. Due to this, there is a huge downsizing of the conventional fleet as seen in the variables in the figure. In this scenario as well, it can be observed that both variables show plausible behavior by not taking a negative value.

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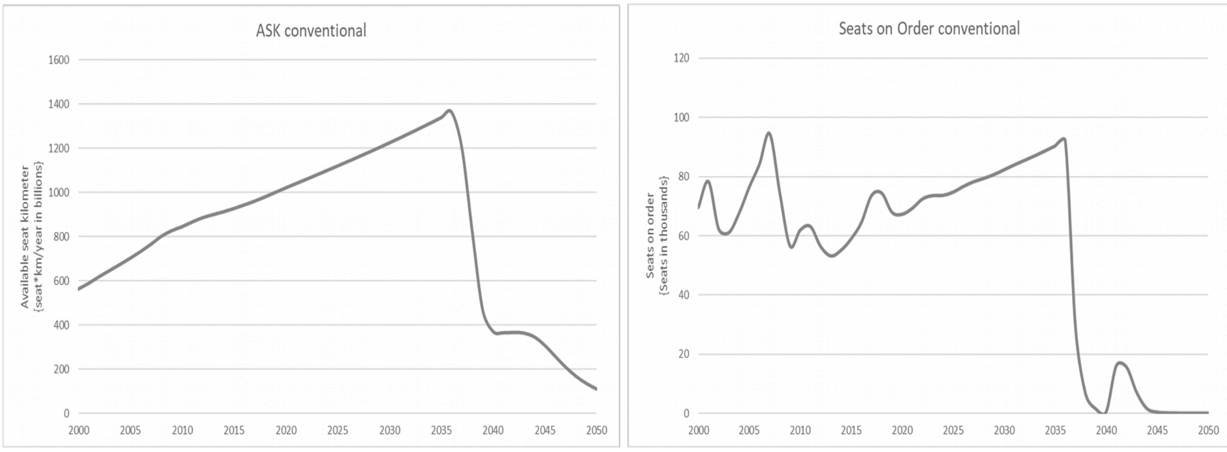

Figure 5: Results of extreme policy: high subsidy.

Note. *The model files of the Vensim [6] implementation and the used data can be found alongside this document.*

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